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(54) Abstract Title

Angle dependent surface multiple attenuation for two - component marine bottom sensor data

(57) An angle dependent filter for two-component sensor data allows for attenuation of free surface multiples. Typical sensors are hydrophones and geophones. The method decomposes the recorded dual sensor data into upgoing and downgoing wavefields by combining the recorded pressure at the hydrophone with the vertical particle velocity from the geophone recorded at the ocean floor. Surface multiple attenuation is accomplished by application of an incident angle dependent deconvolution of the downgoing wavefield from the upgoing wavefield. The method uses an angle dependent filter to calibrate the geophone response so that the different coupling of the two instruments and associated noise are taken into account.

In a further embodiment, a method of attenuation of multiple reflections in seismic data is provided. The seismic data comprises pressure data and particle velocity data. The method comprises deconvolving the seismic data, and applying a moving average operator to the seismic data.

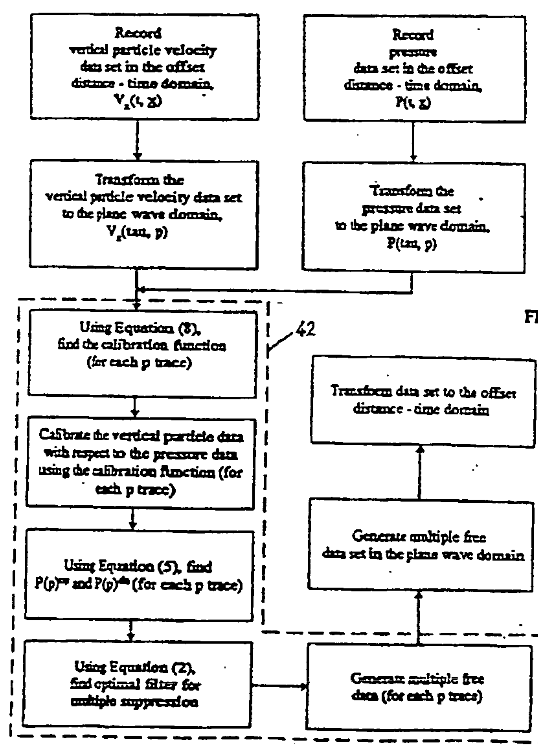

FIG. 3

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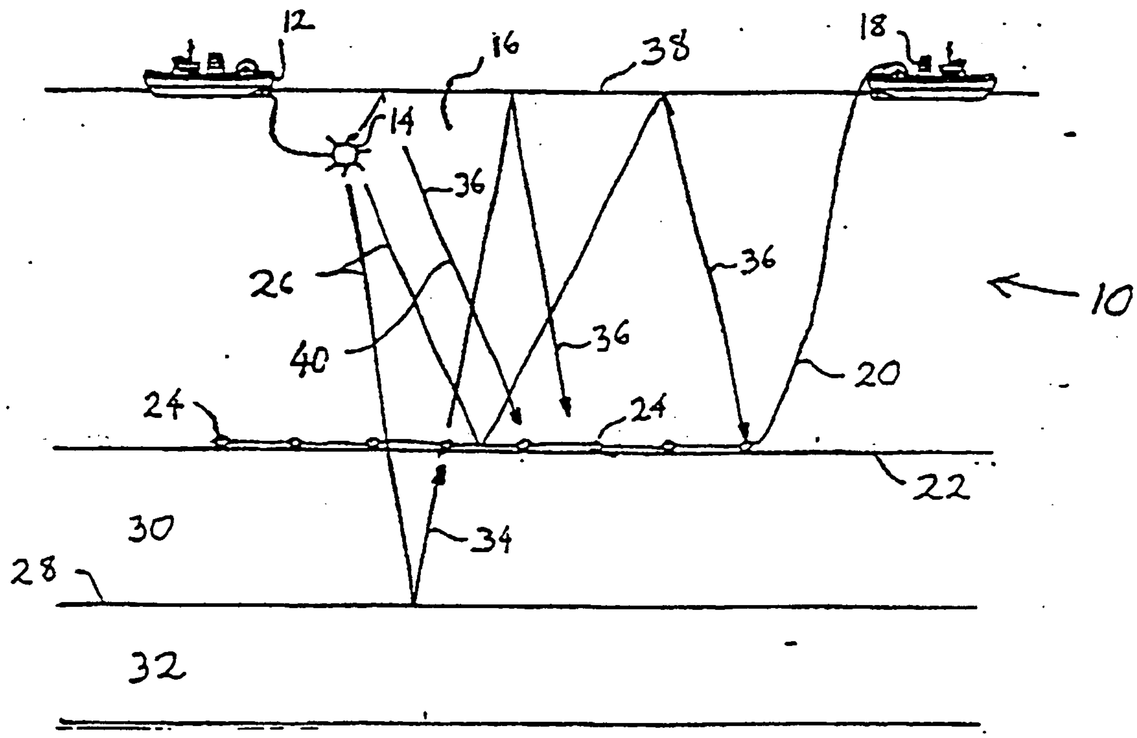


FIG. 1

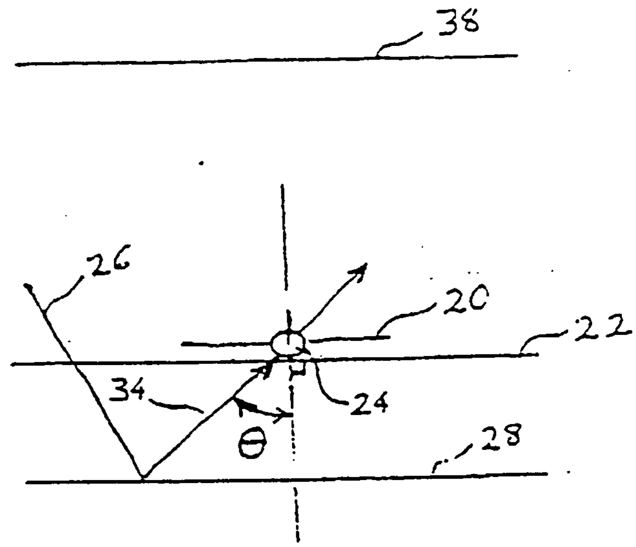
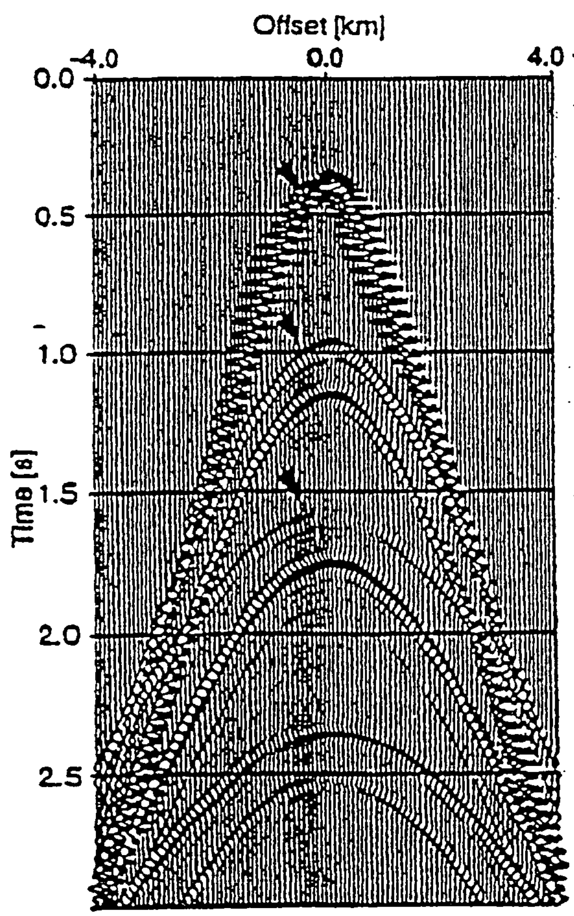


FIG. 2



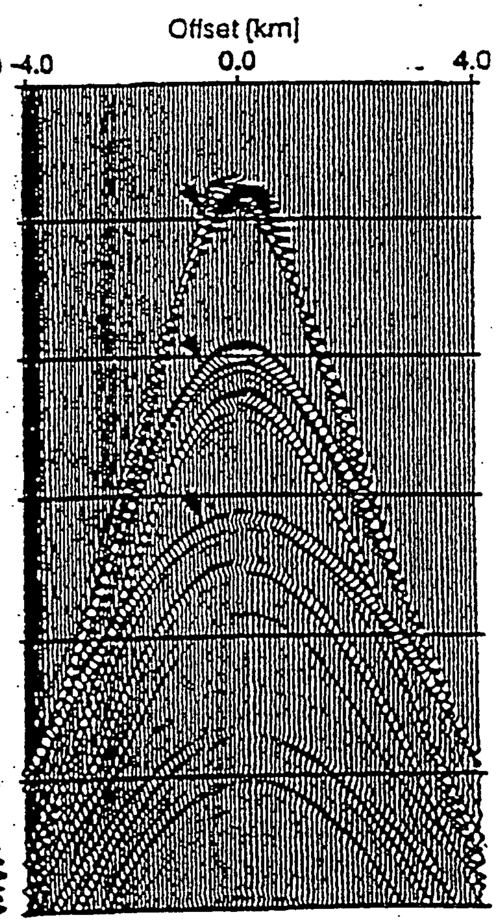
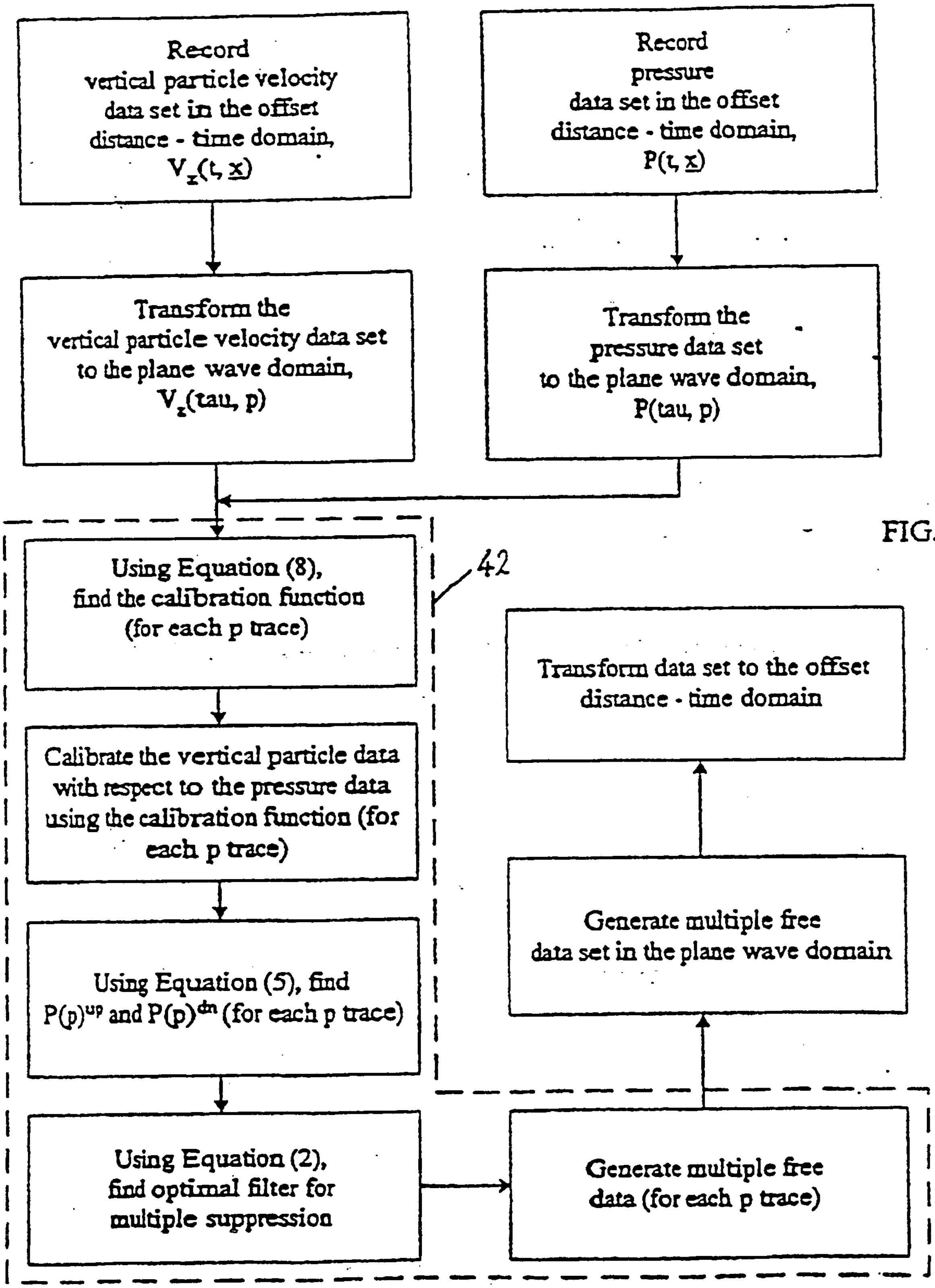


FIG. 4a

FIG. 4b


Record vertical particle velocity data set in the offset distance - time domain, $V_z(t, \underline{x})$
Record pressure data set in the offset distance - time domain, $P(t, \underline{x})$
Transform the vertical particle velocity data set to the plane wave domain, $V_z(tau, p)$
Transform the pressure data set to the plane wave domain, P(tau, p)
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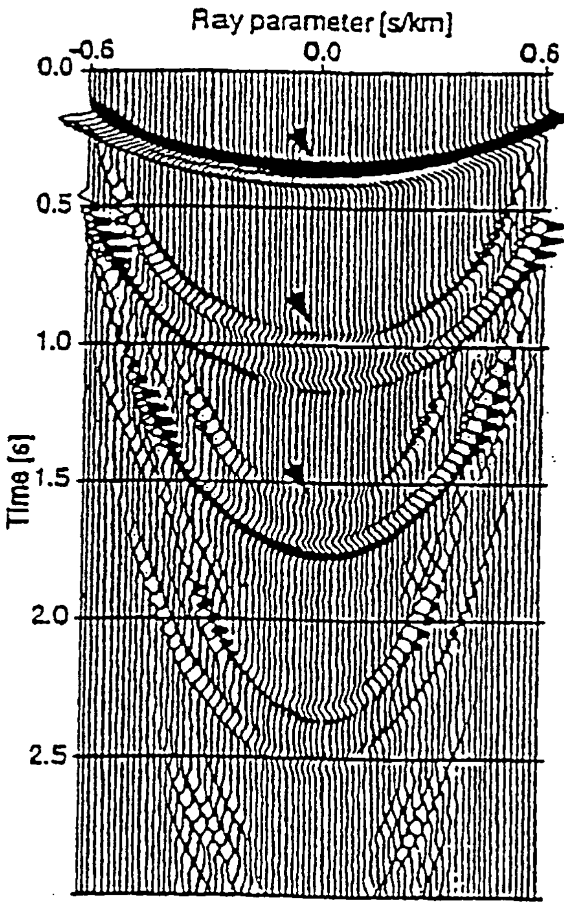
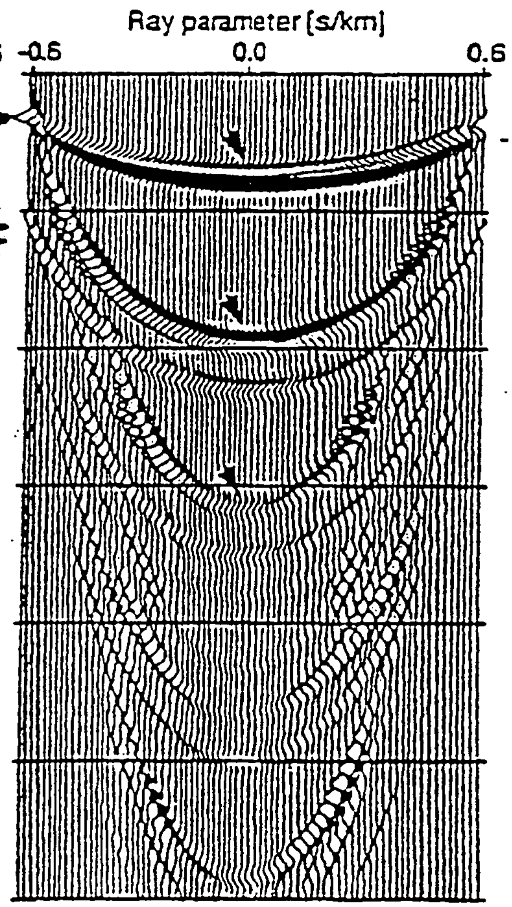
Using Equation (8), find the calibration function (for each p trace)
Calibrate the vertical particle data with respect to the pressure data using the calibration function (for each p trace)
Using Equation (5), find $P(p)^{up}$ and $P(p)^{dn}$ (for each p trace)
Using Equation (2), find optimal filter for multiple suppression
Generate multiple free data (for each p trace)
Generate multiple free data set in the plane wave domain
Transform data set to the offset distance - time domain

FIG. 3



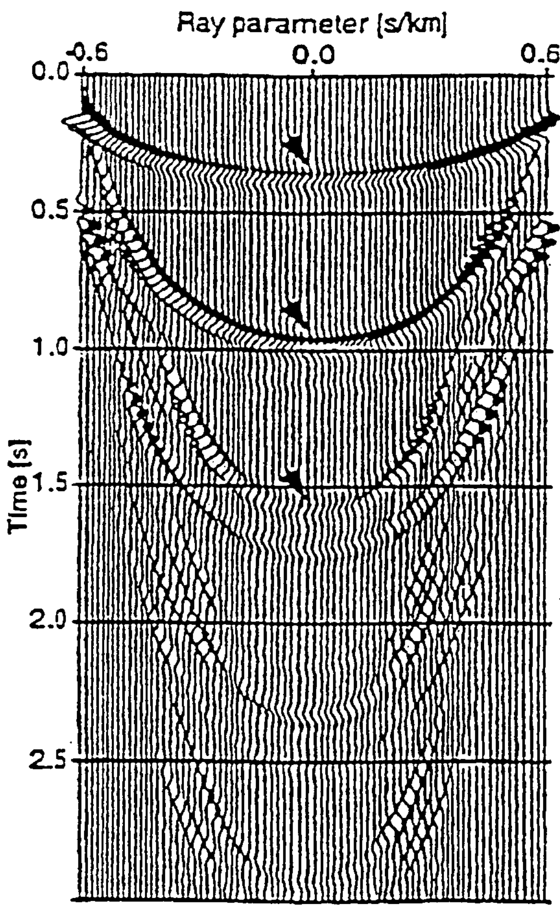
Ray parameter [s/km]
-0.6
0.0
0.6
0.0
0.5
1.0
1.5
2.0
2.5
Time [s]

FIG. 5a



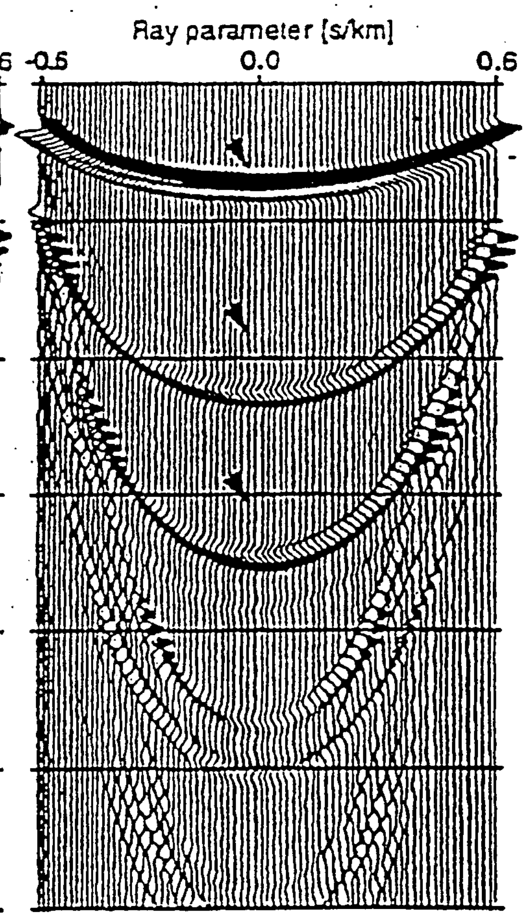
Ray parameter [s/km]
-0.6
0.0
0.6

FIG 5b



Ray parameter [s/km]
-0.6
0.0
0.6
0.0
0.5
1.0
1.5
2.0
2.5
Time [s]

FIG. 6a



Ray parameter [s/km]
-0.6
0.0
0.6

FIG. 6b

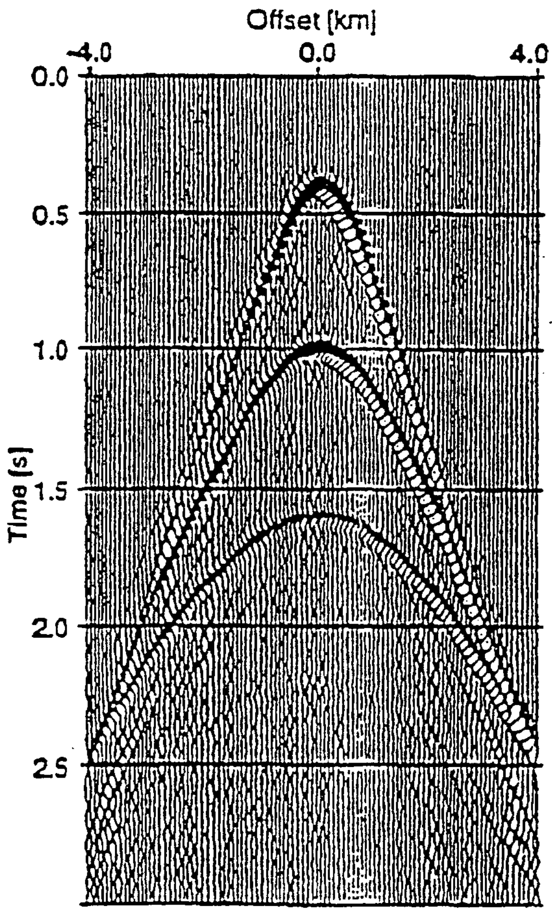


FIG. 7a

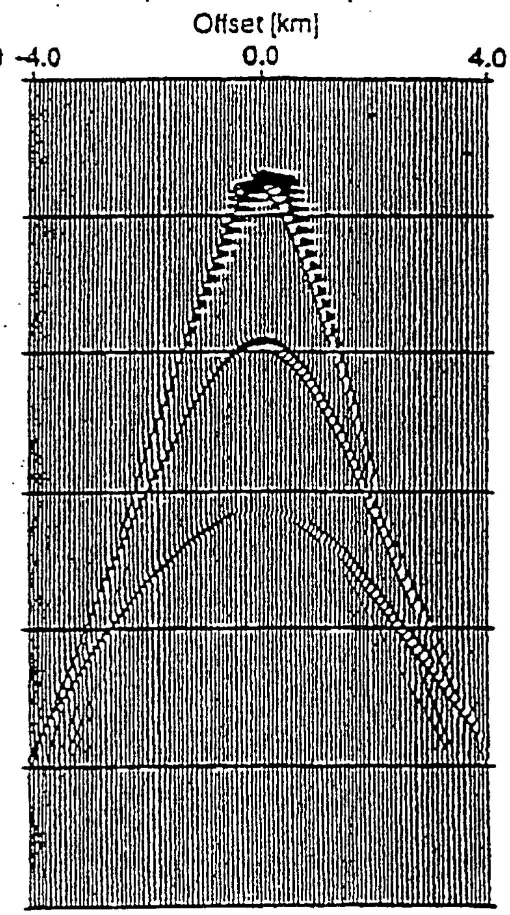


FIG. 7b

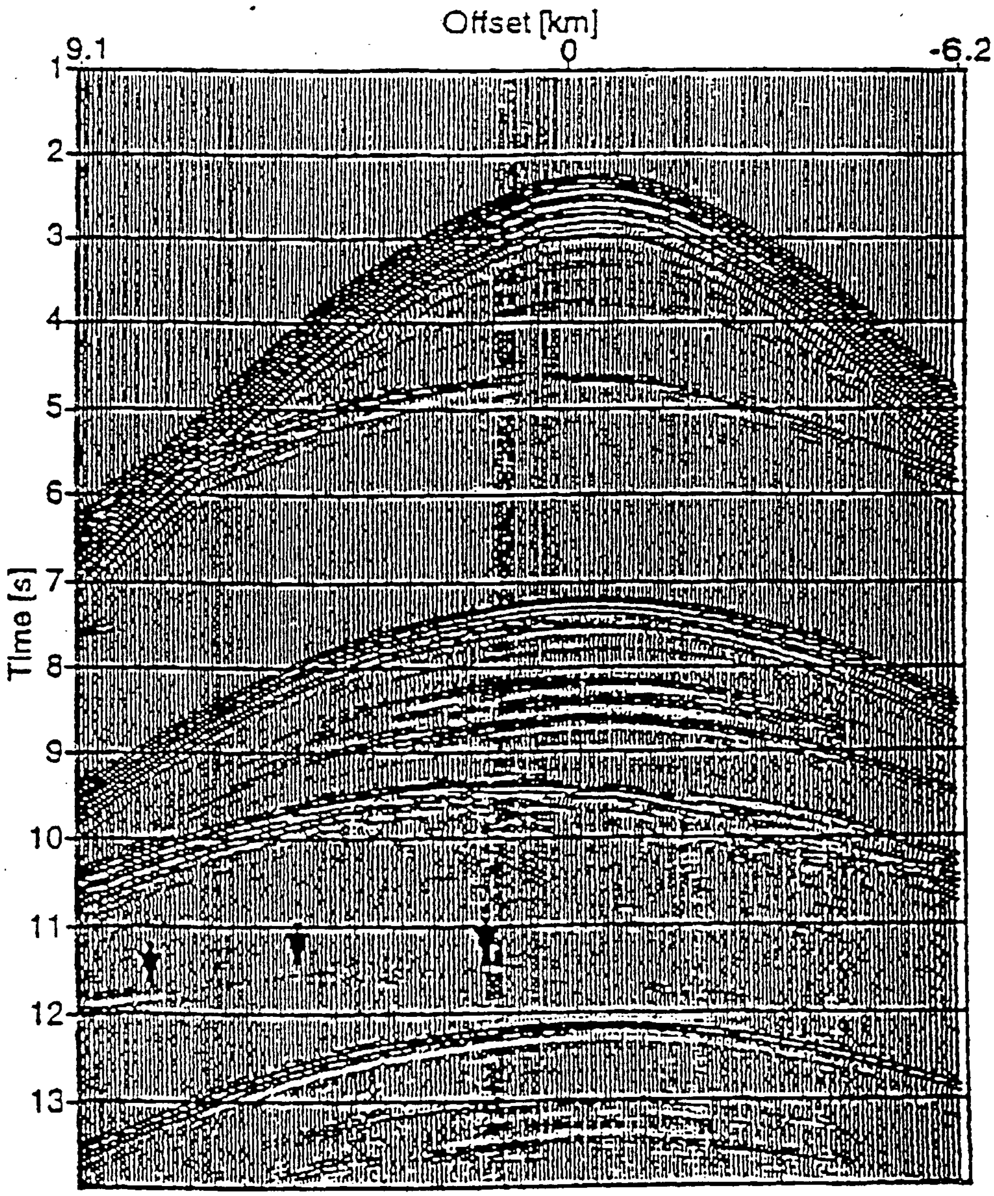


FIG 8

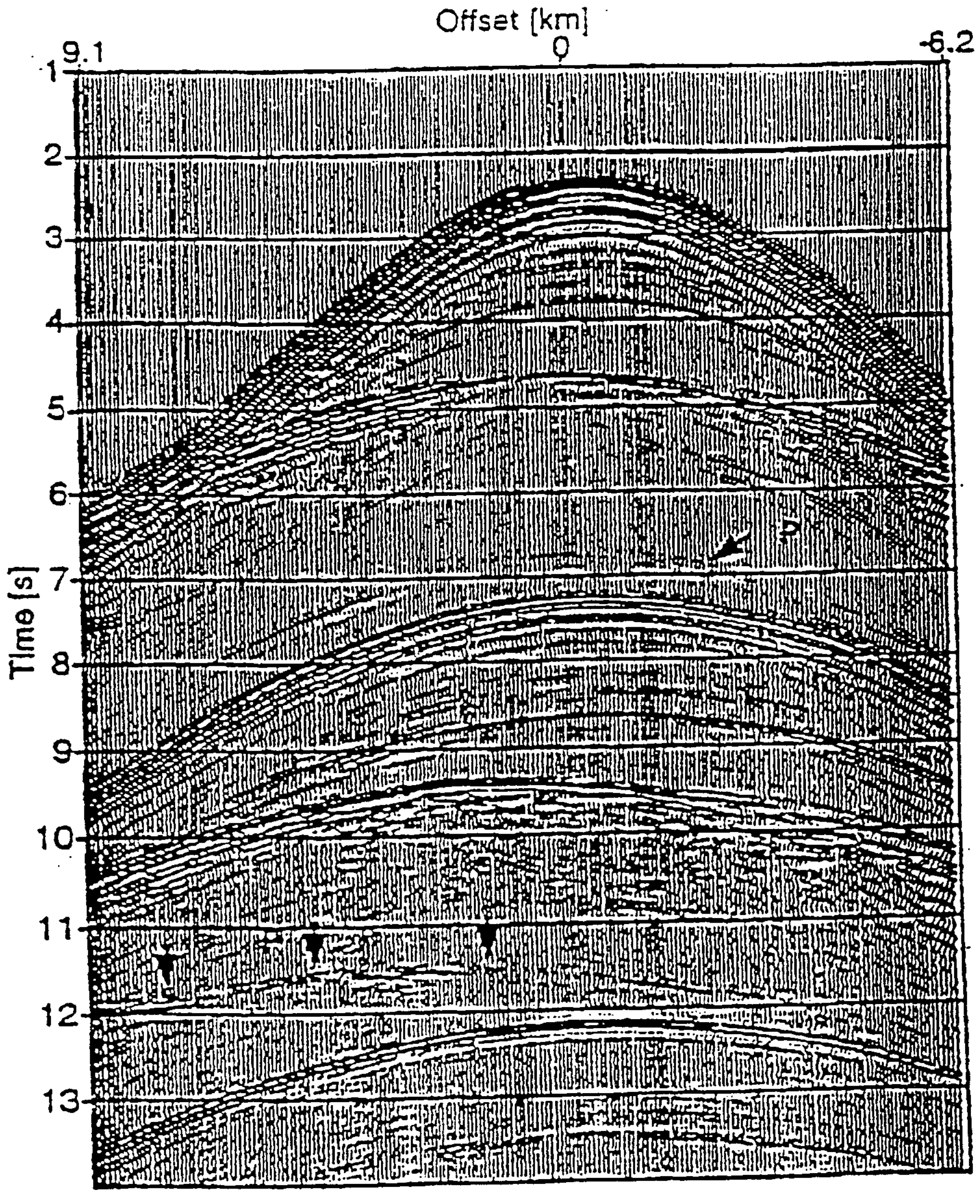


FIG. 9

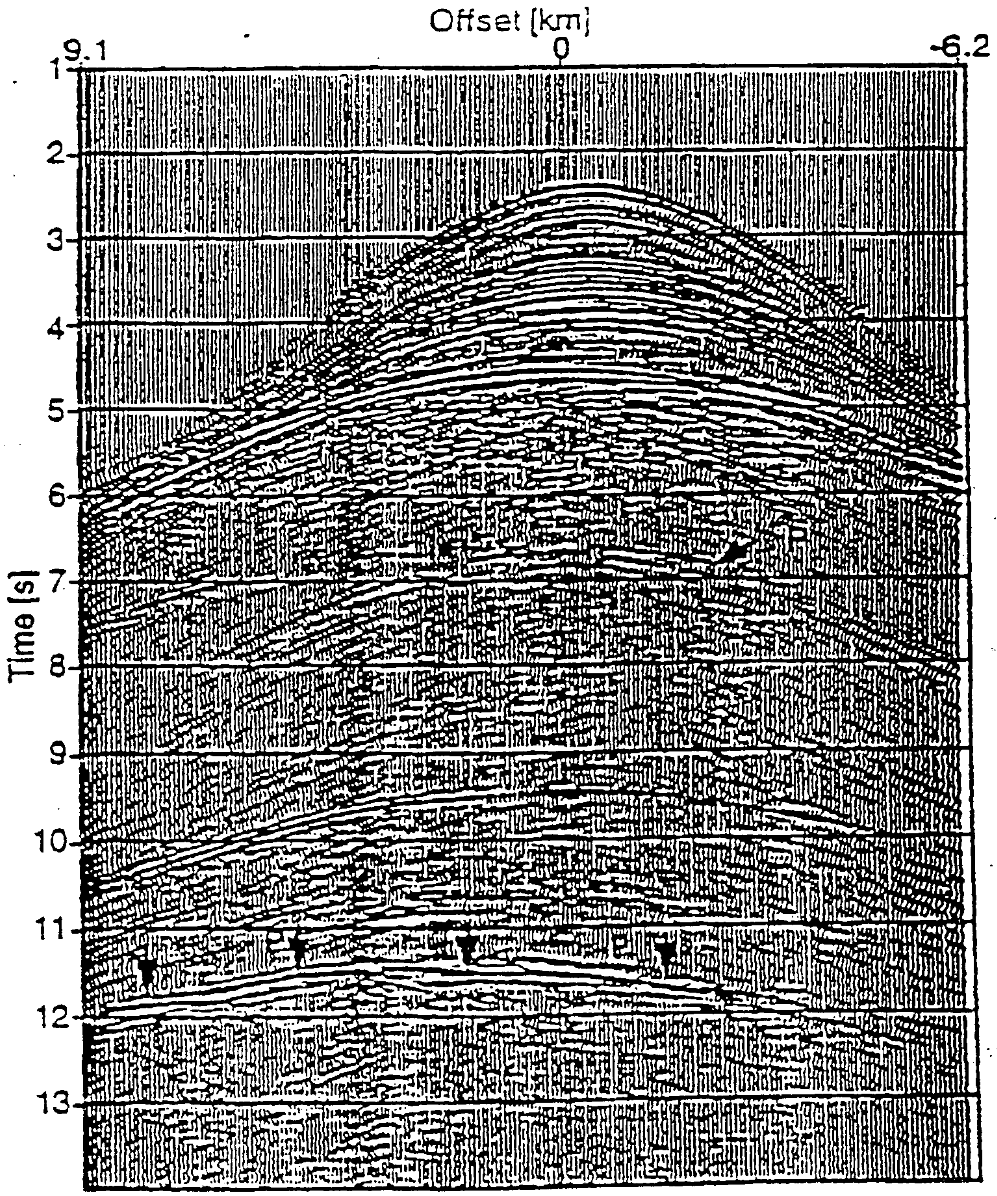


FIG. 10

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ANGLE DEPENDENT SURFACE MULTIPLE ATTENUATION FOR TWO-COMPONENT MARINE BOTTOM SENSOR DATA

The present invention relates generally to marine seismic exploration, and more particularly to a marine seismic measurement system that allows for attenuation of free surface multiples in two-component marine bottom sensor data.

Marine seismic wave measurement systems are used to take seismic profiles of underwater geological configurations. One procedure of marine seismic measurement involves the use of a marine bottom cable. Surveys using marine bottom cables are often employed in areas that are populated with numerous obstacles, such as drilling and production platforms. In a procedure using marine bottom cable, bottom cables are deployed along the marine bottom. Often, multiple cables are deployed in parallel. Each bottom cable has a plurality of sensor pairs placed at regular intervals along the cable. Each sensor pair contains a pressure sensor, such as a hydrophone, and a particle velocity sensor, such as a geophone. A gimbal mechanism within each geophone ensures that the sensing elements of the geophones are vertically oriented.

Acoustic energy is generated in the vicinity of the marine bottom cables using an acoustic energy source such as an air gun array or a marine vibrator array. An air gun discharges air under very high pressure into the water. Marine vibrators typically include a pneumatic or hydraulic actuator that causes an acoustic piston to vibrate at a range of selected frequencies. The vibrations of the acoustic vibrator produce pressure differentials in the water that generate acoustical energy pulses. Source acoustical waves travel downward through the water and into the earth as seismic waves. The source waves strike interfaces between formations in the earth. A portion of the source wave is reflected upwards from the interface towards the marine bottom. The sensor array on the marine bottom receives the reflected waves and converts the waves into signals that are recorded as sensor data. The sensor data is processed to provide information about the structure of the formations beneath the marine bottom.

The sensor array receives not only the reflected waves of interest, but also the source waves and reverberated waves. Reverberated waves are waves that have been

reflected from the water-air interface back towards the marine bottom. Such reverberated waves are referred to as free surface multiples or surface multiples. The free surface multiples may be significant in amplitude and may be difficult to differentiate from the desired reflected waves.

The use of dual sensor measurements, namely pressure and vertical particle velocity, allow for the attenuation of free surface multiples. U.S. Pat. Nos. 5,163,028; 5,365,492; 5,524,100, and 5,621,700 describe methods of attenuating free surface multiples, and each of these patents are incorporated by reference as if fully set forth herein. The methods of attenuating free surface multiples detailed in the above referenced patents do not adequately take into consideration the angle dependence of the upgoing and downgoing wavefields. Also, the methods of attenuating multiples detailed in the above referenced patents do not adequately take into consideration the angle dependency of the response of each sensor of a sensor pair. The use of methods of attenuating multiples that do not consider both the angle dependency of the upgoing and downgoing wavefields and the angle dependency of the response of each sensor of a sensor pair may lead to inaccurate determinations of the formations present beneath the marine bottom.

Existing methods of deconvolution for multiple attenuation of dual sensor data carry out the calibration and deconvolution filter in the distance-time domain, (x,t). The basic equations for deconvolution of upgoing and downgoing waves are valid only in the angle (plane wave) domain. Seismograms recorded from a single shot will have energy propagating at all possible angles, so processing data in the distance-time domain can only have limited success.

SUMMARY OF THE INVENTION

The problems outlined above are in large part to be solved by a system and method of marine seismic exploration that takes into account angle dependencies during the processing of two-component sensor data. Consideration of the angle dependencies of upgoing wavefields, downgoing wavefields, and the sensor enhance the attenuation of free surface multiples that are present in two-component sensor data. The ability to provide enhanced attenuation of free surface multiples allow for more accurate determination of the formations present beneath a marine bottom.

In one example embodiment, a method is used to decompose the recorded dual sensor data into upgoing and downgoing wavefields in the plane wave domain. The

method finds an angle dependent calibration factor that allows the calibration of the recorded pressure data with respect to the recorded vertical particle velocity data. The angle dependent calibration factor takes into consideration the angle dependencies of the hydrophone and the geophone, as well as noise associated with the recording geometry. Attenuation of multiples is accomplished by application of an incident angle dependent deconvolution of the downgoing wavefield from the upgoing wavefield calculated from the calibrated pressure and vertical particle velocity data.

In a further embodiment, a method of attenuation of multiple reflections in seismic data is provided. The seismic data comprises pressure data and particle velocity data. The method comprises deconvolving the seismic data, and applying a moving average operator to the seismic data.

In a further embodiment, a system for attenuation of multiple reflections in seismic data is provided. The seismic data comprises pressure data and particle velocity data. The system comprises means for deconvolving the seismic data, and means for applying a moving average operator to the seismic data.

In a further embodiment, seismic data is provided. The seismic data is processed by a method comprising deconvolving the seismic data, and applying a moving average operator to the seismic data.

BRIEF DESCRIPTION OF THE DRAWINGS

Further advantages of the present invention will become apparent to those skilled in the art with the benefit of the following detailed description of example embodiments and upon reference to the accompanying drawings in which:

FIG. 1 is an illustration of a marine seismic survey system;

FIG. 2 is an illustration of a primary wave impinging a sensor pair;

FIG. 3 is a flow diagram representing a method of processing marine seismic survey data that takes into consideration the angle dependency of the sensor response and the angle dependency of the upgoing and downgoing wavefields;

FIG. 4a and 4b show pressure and vertical velocity data, respectively, from synthetic shot data for a 1-D four layer model;

FIG. 5a and 5b show the data represented in Figures 4a and 4b transformed to the plane wave domain;

FIG. 6a and 6b show the calculated separated upgoing wavefield and the corresponding calculated downgoing wavefield, respectively.

FIG. 7a shows the multiple attenuation results in the distance-time domain;

FIG. 7b shows the location of the simulated primaries of the model;

FIG. 8 shows hydrophone data from an offshore ocean bottom experiment in the South China Sea;

FIG. 9 shows corresponding geophone data for the ocean bottom experiment in the South China Sea depicted in Figure 8; and

FIG. 10 shows the multiple attenuation results obtained after processing the data represented in Figures 8 and 9.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS OF THE PRESENT INVENTION

With reference to the drawings, and particularly to Figure 1, a marine seismic survey system is generally designated by reference numeral 10. In one embodiment of the present invention, the system 10 includes a seismic survey ship 12 that tows an acoustic energy source 14 through a body of water 16. In various embodiments, the acoustic energy source is an array of acoustic energy sources. In alternate embodiments, the acoustic energy source is an air gun, a marine vibrator, or another device that generates acoustic waves. The construction and operation of acoustical energy sources is well known in the art and is not described in detail herein. The activation of the acoustic energy source is referred to as "shooting."

In a further embodiment, the system 10 includes receiving ship 18. The receiving ship 18 deploys bottom cable 20 on marine bottom 22. The receiving ship deploys an array of bottom cables in parallel lines. Each bottom cable 20 carries at least one sensor pair 24, and preferably, each bottom cable carries a plurality of sensor pairs. Each sensor pair 24 includes a pressure sensing transducer, such as a hydrophone, and a particle velocity sensor, such as a geophone. As is well known in the art, each marine geophone includes a gimbal mechanism to ensure that the sensing element of the geophone is vertically oriented during use. In a further embodiment, each hydrophone and geophone sends separate data signals to the receiving ship 18. The data is recorded by a multi-channel seismic recording system that selectively amplifies, conditions, and records time-varying electrical signals. In still a further embodiment, the system also digitizes the received signals to facilitate signal analysis. Any of a variety of seismic recording systems is used to record the data.

To take a marine seismic survey, the receiver ship 18 positions the bottom cable 20 on the marine bottom 22. In an embodiment, shooting takes place while the survey ship 12 moves at a constant speed along a set of survey lines with respect to the cable 20. The location and depth of each sensor pair 24, and the location of the acoustical energy source 14 at the time of each shot are recorded. After the survey ship 12 completes the survey line, the receiving ship 18 retrieves the cable 20 and re-deploys the cable in a new position. After re-deployment of the cable 20, the survey ship 12 shoots another set of survey lines.

During data collection, seismic waves 26 generated by the source 14 travel away from the source. Portions of the waves travel downward and into the land beneath the marine bottom 22. The waves are reflected off of interfaces between subterranean formations, such as interface 28 between subterranean formations 30 and 32 as shown in Figure 1. Reflected waves 34 from the interfaces travel upwards and impinge upon a sensor pair 24. The sensor pairs 24 detect the reflected waves 34 and transmit signals along the cable 20 to the receiving ship 18. The receiving ship 18 records the data so that the data can be subsequently processed to map the location of interfaces 28 between subterranean formations.

The sensor pairs 24 receive not only the reflected waves 34, which are also known as primaries, but also the source waves 26 and free surface multiples 36. The free surface multiples 36 may be significant in amplitude and may be difficult to differentiate from the desired reflected waves 34. Free surface multiples that originate from the source, contact the air/surface interface 38, and travel towards the marine bottom are referred to as ghosts 40.

In most marine seismic data acquisition situations, the energy source 14 is placed above the marine bottom 22. All upgoing wavefields in the data result from reflections of downgoing incident waves to the marine bottom. Mathematically, this is formulated by the following convolution,

$$d(t)^{up} = r(t) \otimes d(t)^{dn} \tag{1}$$

where $d(t)^{up}$ are the upgoing wavefields, which can be either primaries 34 or multiples 36; and $d(t)^{dn}$ is the downgoing wavefield, which may be direct transmission from the source 26 or reflection events 36 (source, primaries or multiples) that are bounced back at the air/surface interface 38 (receiver ghosts). In equation (1), $r(t)$ is the reflectivity of

the structure, which includes those reflections taking place both at the marine bottom 22 and inside the land structure below the marine bottom; and t is the wavefield traveltime. The reflectivity, r(t), also includes internal multiple reflections.

The reflectivity, r, is obtained by deconvolving the downgoing wavefield from the upgoing wavefield. In one example embodiment, in the frequency domain, this is represented by a simple division:

$$R(\omega) = D(\omega)^{up} / D(\omega)^{dn} \tag{2}$$

where $R(\omega)$, $D(\omega)^{up}$, and $D(\omega)^{dn}$ are the Fourier transforms with respect to time of r(t), $d(t)^{up}$, and $d(t)^{dn}$, respectively.

The deconvolution based multiple attenuation method given in equation (2) requires separated upgoing and downgoing wavefields. The upgoing and downgoing wavefields are represented by the upgoing and downgoing pressure, or by the upgoing and downgoing vertical particle velocity.

In the above description, the angle dependency of the propagating waves was suppressed to present the fundamental ideas behind processing two-component marine bottom sensor data. The development below takes into account angle dependence.

In various embodiments, seismic data is recorded in the offset distance-time domain. Offset distance is the horizontal distance between the location of a sensor pair 24 and the location of the acoustic energy source 14 at the time of a shot. The seismic data recorded by a sensor pair 24 is a record of the variation in pressure, as measured by hydrophones, and vertical particle velocity, as measured by geophones, taken as a function of source-to-receiver offset distance and time. In a further embodiment, the acoustic energy source 14 is considered to be a point source. In practice, the source 14 will have a directivity that is angle dependent. In still a further embodiment, the response of a source is synthesized by summing the responses from a series of plane waves each characterized by the propagation angle of the plane wave. In yet a further embodiment, the source generated data recorded in the offset-time domain is decomposed into plane waves by means of a Radon transform. If $u(\underline{x},\omega)$ are the recorded data where $\underline{x}$ is the vector representing the source-to-receiver offset distance, and ω is the frequency, the plane wave response is given by:

$$\underline{u}(\tau,\underline{p}) = \int d\omega \int d\underline{x}\, u(\omega,\underline{p})\, e^{-i\omega(t-\underline{p}\cdot\underline{x})},$$

where $\underline{p}$ is the vector ray-parameter, and τ is the offset time, or $\tau = t - \underline{p}\,\underline{x}$. In a two-dimensional geometry, $\underline{p}=p_x=p=\sin\theta/\alpha$. The angle θ is the angle of propagation, and α is the velocity of sound in the medium. The angle of propagation θ is illustrated in Figure 2 for a primary wave 34.

In a further embodiment, in the frequency-ray-parameter domain, the pressure recorded by hydrophones is given by the equation:

$$P(\omega,p) = c_1(p)(1+R(\omega,p))^{-1} (e^{-i\omega qh} + R(\omega,p)e^{-i\omega qh})S(\omega,p). \qquad (3)$$

The corresponding vertical velocity geophone data in the frequency-ray parameter domain is given by the equation:

$$V_z(\omega,p) = c_2(p)(1+R(\omega,p))^{-1}(R(\omega,p)^{-i\omega qh} - e^{-i\omega qh})S(\omega,p), \qquad (4)$$

where p is the ray-parameter, θ is the angle of propagation; α is the sound velocity in the medium; R is the reflectivity of the structure referenced to the water surface, which includes the response of both the primaries and internal multiples; h_r is the receiver depth; q is the vertical slowness, or $q = ((1/\alpha^2 - p^2))^{1/2})$; S is the source wavelet with source side ghosts; and c_1 and c_2 are two incident angle dependent coefficients defined by the ray-parameter and the parameters of the medium.

In a further embodiment, the upgoing and downgoing wavefields are obtained by combining the pressure and the vertical components of the vertical particle velocities in equations (3) and (4) to yield:

$$P(p)^{up} = (1/2)\,(P(p) + c(p)V_z(p)),\ \ P(p)^{dn} = (1/2)\,(P(p) - c(p)\,V_z(p))\ , \qquad (5)$$

where c(p) is a function defined by the parameters of the medium.

In some embodiments, equation (5) is considered to be an equation describing a system wherein the hydrophones and the geophones are perfectly coupled to the environment, wherein the geophones have the same response characteristics, and wherein the environment surrounding the sensor pair 24 is noise free. Direct application of equation (5) may not yield good results because, in reality, a sensor pair is not perfectly coupled to the environment, the instrument response characteristics of hydrophones and geophones are not the same, and sensor pairs 24 are not located in noise free environments. In further embodiments, the angle dependency of the sensor pairs require

that the geophone data be calibrated to the pressure data, or vice versa, before the upgoing and downgoing wave components are determined.

In a further embodiment, from equations (3) and (4), the following equation are derived:

$$\hat{S}(\omega,p) = (1/2)[(1+Z(\omega,p))]P(\omega,p)[(1-Z(\omega,p))]V_z(\omega,p) \qquad (6)$$

where $Z(\omega,p)$ is a filter and $\hat{S}(\omega,p)$ is the temporal Fourier transform of the time delayed source function, which is a function of the source excitation function $S(\omega,p)$, and is given by the equation:

$$\hat{S}(\omega,p) = (1/(2q\alpha^2))e^{-i\omega qh}\,(e^{-i\omega qh} - e^{-i\omega qh}\,S(\omega,p))$$

The term $\hat{S}(\omega,p)$ contains the source excitation function $S(\omega,p)$, the source side ghosts, and the transmission operator.

Since the source excitation function is always of finite duration in real data, there must exist a time $T_o(p)$, such that:

$$\hat{s}(t,p) = 0, \text{ if } t > t_0 + h_r/\alpha \qquad (7)$$

where $\hat{s}(t,p)$ is the inverse temporal Fourier transform of $\hat{S}(\omega,p)$, which is the delayed source function.

In a further embodiment, equation (7) allows the hydrophone data and the geophone data to be calibrated so that the delayed source function is optimal. The calibration filter is designed such that the delayed source function defined in equation (7) will have minimum energy after a certain time. The time will include the source excitation function time duration and the sum of the propagation time of the energy of the source to go to the receiver and back to the surface. In a further embodiment, the calibration function, $f(\omega,p)$, is found by solving the following equation and constraint:

$$\left\| F^{-1}[(1+Z(\omega,p))P(\omega,p) + f(\omega,p)(1-Z(\omega,p))]V_z(\omega,p) \right\| = \text{minimum} \qquad (8)$$
$$t > T_0 = t_0 + h_r/\alpha$$

where F^{-1} stands for the inverse Fourier transform operator. In a further embodiment, a numerical method of solving for the calibration function in a least squares sense involves solving a system of equations with Toepliz structure to find a value for the calibration

function for a given value of p. A person having ordinary skill in the art will recognize that in alternate embodiments, many methods are used to solve the equation and constraint of equation (8) to yield the optimum angle dependent calibration function.

Finding the calibration function allows for the calibration of hydrophone and geophone data. In yet a further embodiment, angle dependent multiple attenuated data is then obtained by forming and using an optimal filter from the calibrated data by application of equations (5) and (2).

The methodology for one embodiment of processing two-component marine sensor data is shown diagrammatically in Figure 3. Figure 3 shows that the data is first collected and recorded in the offset distance-time domain. The data is then transformed to the plane wave domain, τ-p. Each p trace of the transformed data set is converted into multiple free data by the application of the steps illustrated within block 42. For each p trace of the transformed data set, a calibration function is numerically calculated based on equation (8). The calibration function is then used to calibrate the vertical particle velocity data with respect to the pressure data. The calibrated data is then used to find information corresponding to the upgoing and downgoing wavefields. The upgoing and downgoing wavefield information is used to numerically solve for an optimal filter to suppress multiples by applying Equation (2). The optimal filter for the p trace is then used to generate multiple free data for the p trace. The generated multiple free data for each p trace forms a multiple free data set. The multiple free data sets are transformed back to the offset time domain.

Figures 4-7 show an application of one example embodiment of processing two-component marine seismic data to a 1-D four layer acoustic model. The hydrophone and geophone data are shown in Figures 4a and 4b. Figure 5a and 5b show the τ-p transformation of the data. The pressure shown in Figure 5b is then decomposed into an angle dependent estimate of the upgoing wavefield and the downgoing wavefield by applying equation (5). The upgoing wavefield is shown in Figure 6a, and the downgoing wavefield is shown in Figure 6b. The reflectivity of the model is computed by deconvolving the downgoing wavefield from the upgoing wavefield in the τ-p domain. Following an inverse τ-p transform, the final result in the x-t domain is obtained and shown in Figure 7a. By comparing the results shown in Figure 7a with the original data sets shown in Figures 4a and 4b, and with the simulated primary reflections of the model as shown in Figure 7b, it is seen that the method of processing two-component marine

seismic data attenuates the multiples in the data and recovers the reflectivity of the model. In Figures 4-7, the arrows point out the location of the three primary interfaces, which represent the water-land interface, and two subterranean interfaces.

One example embodiment of the method has also been applied to ocean bottom dual sensor data collected in the South China Sea. Figure 8 shows the pressure data, and Figure 9 shows the corresponding vertical particle velocity. After transforming to the plane wave domain, the geophone data is calibrated before separating the upgoing and downgoing wavefields. The final result of multiple attenuation is shown in Figure 10. For comparison with the original data, the result has been convolved with a zero phase wavelet derived from the autocorrelation of each p trace in the hydrophone data before inverse τ-p transform. As shown in Figure 10, the multiples have been attenuated, and more importantly, the primary reflections, which are marked by arrows, have been preserved.

The primary reflections were not strongly visible in the original data due to the presence of strong multiples.

In an even further embodiment of the present invention, the signal is conditioned before the multiple elimination procedure is applied. In an alternate embodiment, the signal is conditioned after the multiple elimination procedure is applied.

In still a further embodiment, angle dependence is contained in the vertical velocity plane wave seismogram and the pressure plane wave seismogram. Differences in the response are due to the differences in wave types recorded and in the recording sensors. As described above, in various embodiments, minimizing the source time duration defines an angle dependent filter, which is used to calibrate the two plane wave seismograms.

In still a further embodiment, a conventional predictive deconvolution is applied to the plane wave pressure and vertical seismograms. In a further embodiment, the predictive deconvolution is applied in the plane wave domain. In alternate embodiments, the deconvolution is applied to the data together or independently. In one embodiment, the result is that each will now have the short time duration components of the angle dependent responses, which arise from each sensor (geophone and hydrophone) removed.

In still a further embodiment, following the angle dependent deconvolution, each seismogram is bandpass filtered to the same frequency band. In yet a further

embodiment, an amplitude calibration is performed for the deconvolved and bandpass filtered plane wave pressure and vertical velocity seismograms. In one embodiment, the amplitude calibration uses time signal moving average operators for each plane wave component to define the mean signal level. In further example embodiments, the time signal moving averaging is achieved through the following equations:

$$\widehat{P}(\tau_i, p) = \frac{1}{2k} \sum_{j=i-k}^{i+k} P(\tau_j, p) \qquad (9)$$

$$\widehat{V}_z(\tau_i, p) = \frac{1}{2k} \sum_{j=i-k}^{i+k} V_z(\tau_j, p) \qquad (10).$$

In still a further embodiment, an inter-seismogram calibration further comprises comparing an average of pressure seismograms with an average of vertical velocity seismograms for each pair (pressure and vertical velocity) of plane wave seismograms. In yet a further embodiment, equations (9) and (10) are used in equation (8) for calibration.

In another embodiment, the vertical velocity signal average is normalized to that of the pressure average to define the amplitude correction on a time sample by time sample basis. In a further embodiment, the time signal moving average operator length k is varied to achieve the optimum calibration. Predictive deconvolution followed by moving averaging of signals applied to plane wave seismograms introduces stability and results in robust estimates of multiple free seismograms.

In a further embodiment, a method of attenuation of multiple reflections in seismic data is provided. The seismic data comprises pressure data and particle velocity data. The method comprises deconvolving the seismic data, and applying a moving average operator to the seismic data.

In a further embodiment, said deconvolving the seismic data further comprises applying a predictive deconvolution to the seismic data. In a further embodiment,, applying a predictive deconvolution to the seismic data further comprises applying a predictive deconvolution to the pressure data and the particle velocity data independently. In alternate embodiments, a deconvolution is applied such as a spiking deconvolution, gapped deconvolution, statistical deconvolution, deterministic

deconvolution or any other deconvolution that will occur to those of ordinary skill in the art.

In still a further embodiment, the method further comprises bandpass filtering the seismic data. In a further embodiment, the method further comprises bandpass filtering the pressure data and the particle velocity data independently.

In a further embodiment, the method comprises amplitude calibrating the seismic data. In a further embodiment, said amplitude calibrating further comprises defining a mean signal level.

In a further embodiment, said applying a moving average operator further comprises applying essentially the following formula:

$$\bar{P}(\tau_i, p) = \frac{1}{2k} \sum_{j=i-k}^{i+k} P(\tau_j, p).$$

In a further embodiment, said applying a moving average operator further comprises applying essentially the following formula:

$$\bar{V}_z(\tau_i, p) = \frac{1}{2k} \sum_{j=i-k}^{i+k} V_z(\tau_j, p).$$

In still a further embodiment, a system for attenuation of multiple reflections in seismic data is provided. The seismic data comprises pressure data and particle velocity data. The system comprises means for deconvolving the seismic data, and means for applying a moving average operator to the seismic data. In alternate embodiments, the means for deconvolving the seismic data comprises a computer, a workstation, software, software running on any computer, or any other means for deconvolving the seismic data that will occur to those of ordinary skill in the art. In alternate embodiments, the means for applying a moving average operator to the seismic data comprises a computer, a workstation, software, software running on any computer, or any other means for applying a moving average operator to the seismic data that will occur to those of ordinary skill in the art.

In a further embodiment, said means for deconvolving the seismic data further comprises means for applying a predictive deconvolution to the seismic data. In alternate embodiments, the means for applying a predictive deconvolution to the seismic

data comprises a computer. a workstation, software, software running on any computer, or any other means for applying a predictive deconvolution to the seismic data that will occur to those of ordinary skill in the art.

In a further embodiment, said means for applying a predictive deconvolution to the seismic data further comprises means for applying a predictive deconvolution to the pressure data and the particle velocity data independently. In alternate embodiments, the means for applying a predictive deconvolution to the pressure data and the particle velocity data independently comprises a computer, a workstation, software, software running on any computer, or any other means for applying a predictive deconvolution to the pressure data and the particle velocity data independently that will occur to those of ordinary skill in the art.

In a further embodiment, the system further comprises means for bandpass filtering the seismic data. In alternate embodiments, the means for bandpass filtering the seismic data comprises a computer, a workstation, software, software running on any computer, or any other means for bandpass filtering the seismic data that will occur to those of ordinary skill in the art.

In a further embodiment, the system further comprises means for amplitude calibrating the seismic data. In alternate embodiments, the means for amplitude calibrating comprise a computer, a workstation, software, software running on any computer, or any other means for amplitude calibrating that will occur to those of ordinary skill in the art.

In a further embodiment, said means for applying a moving average operator further comprises means for applying a time signal moving average operator. In alternate embodiments, the means for applying a time signal moving average operator comprises a computer, a workstation, software, software running on any computer, or any other means for applying a time signal moving average operator that will occur to those of ordinary skill in the art.

In a further embodiment, said means for applying a moving average operator to the seismic data further comprises means for inter-seismogram averaging. In alternate embodiments, the means for inter-seismogram averaging comprises a computer, a workstation, software, software running on any computer, or any other means for inter-seismogram averaging that will occur to those of ordinary skill in the art.

In a further embodiment, means for inter-seismogram calibration further comprises means for comparing an average of the particle velocity data and the pressure data. In alternate embodiments, the means for comparing an average of the particle velocity data and the pressure data comprises a computer, a workstation, software, software running on any computer, or any other means for comparing an average of the particle velocity data and the pressure data that will occur to those of ordinary skill in the art.

In a further embodiment, the system further comprises means for normalizing the particle velocity data. In alternate embodiments, the means for normalizing comprises a computer, a workstation, software, software running on any computer, or any other means for normalizing that will occur to those of ordinary skill in the art.

In a further embodiment, the system further comprises means for normalizing the pressure data. In alternate embodiments, the means for normalizing comprises a computer, a workstation, software, software running on any computer, or any other means for normalizing that will occur to those of ordinary skill in the art.

In a further embodiment, seismic data is provided. The seismic data is processed by a method comprising deconvolving the seismic data; and applying a moving average operator to the seismic data.

CLAIMS

1. A method for attenuation of multiples in marine seismic data, comprising:

creating seismic wavefields in a water environment, each created wavefield generated at a different location;

recording sensor readings from at least one sensor pair, wherein said at least one sensor pair comprises two different types of sensors. wherein said sensor readings are substantially a result of the created seismic wavefields, and wherein said sensor reading form a data set;

calculating angle dependent estimated values for upgoing and downgoing wavefields that generated the data set; and

generating an attenuated multiple data set using the estimated values for the upgoing and downgoing wavefields.

2. The method as defined in claim 1, wherein at least one sensor pair comprises a pressure sensor and a vertical particle velocity sensor.

3. The method of claim 1 or claim 2, wherein calculating angle dependent estimated values for upgoing and downgoing wavefields further comprises:

transforming the data set to a plane wave domain data set;

calibrating the plane wave domain data set using angle dependent calibration functions; and

using the calibrated plane wave domain set to calculate the estimated values for the angle dependent upgoing and downgoing wavefields.

4. A system for generating attenuated multiple data for two-component marine seismic sensor data, comprising:

an acoustic energy source configured to generate an acoustic wavefield;

at least one sensor pair, the at least one sensor pair comprising two types of sensors configured to detect wavefields resulting from the generation of an acoustic wavefield by the acoustic energy source;

a recording system configured to separately record sensor readings from each sensor of the at least one sensor pair as data, the recording system configured to record

the location of the acoustic energy source at a time when the acoustic energy source generates an acoustic wavefield, and said recording system configured to record the location of the at least one sensor pair; and

a data processor configured to analyze the data and produce the attenuated multiple data;

wherein the data processor calculates angle dependent estimated values of upgoing and downgoing wavefields that generated the data set, and wherein the data processor uses the estimated values of the upgoing and downgoing wavefields to generate the attenuated multiple data during use.

5. A method of generating attenuated multiple data from two-component marine seismic data, comprising:

calculating angle dependent estimated values for upgoing wavefields and downgoing wavefields that generated the data; and

generating an attenuated multiple data set using the estimated values for the upgoing and downgoing wavefields.

6. A method of attenuation of multiple reflections in seismic data, wherein the seismic data comprises pressure data and particle velocity data, the method comprising:

deconvolving the seismic data in the plane wave domain; and

applying a moving average operator to the seismic data.

7. The method of claim 6, wherein said deconvolving the seismic data further comprises applying a predictive deconvolution to the seismic data.

8. The method of claim 7, wherein said applying a predictive deconvolution to the seismic data further comprises applying a predictive deconvolution to the pressure data and the particle velocity data independently.

9. The method of any of claims 6 to 8, further comprising bandpass filtering the seismic data.

10. The method of claim 9, further comprising bandpass filtering the pressure data and the particle velocity data independently.

11. The method of any of claims 6 to 10, comprising amplitude calibrating the seismic data.

12. The method of claim 11, wherein said amplitude calibrating further comprises defining a mean signal level.

13. The method of any of claims 6 to 12, wherein said applying a moving average operator further comprises applying a time signal moving average operator using essentially the following formulae:

$$\bar{P}(\tau_i, p) = \frac{1}{2k} \sum_{j=i-k}^{i+k} P(\tau_j, p)$$

$$\bar{V}_z(\tau_i, p) = \frac{1}{2k} \sum_{j=i-k}^{i+k} V_z(\tau_j, p).$$

14. The method of any of claims 6 to 13, wherein said applying a moving average operator to the seismic data further comprises inner-seismogram calibration.

15. The method of claim 14, wherein said inter-seismogram calibration further comprises comparing an average of the particle velocity data and the pressure data.

16. The method of any of claims 6 to 15, further comprising normalizing the particle velocity and pressure data.

17. A system for attenuation of multiple reflections in seismic data, wherein the seismic data comprises pressure data and particle velocity data, the system comprising:

means for deconvolving the seismic data in the plane wave domain; and

means for applying a moving average operator to the seismic data.

18. The system of claim 17, where said means for deconvolving the seismic data further comprises means for applying a predictive deconvolution to the seismic data.

19. The system of claim 17 or claim 18, further comprising means for bandpass filtering the seismic data.

20. The system of any of claims 17 to 19, comprising means for amplitude calibrating the seismic data.

21. The system of claim 20, wherein said means for amplitude calibrating further comprises means for defining a mean signal level.

22. The system of any of claims 17 to 21, wherein said means for applying a moving average operator to the seismic data further comprises means for inter-seismogram calibration.

23. The system of claim 22, wherein said means for inter-seismogram calibration further comprises means for comparing an average of the particle velocity data and the pressure data.

24. The system of any of claims 17 to 23, further comprising means for normalizing the particle velocity and pressure data.

25 Seismic data processed by a method comprising:

deconvolving the seismic data in the plane wave domain; and

applying a moving average operator to the seismic data.

Application No:	GB 0204625.8	**Examiner:**	Robert C Mumford
Claims searched:	1 - 16	**Date of search:**	10 September 2002

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.T): G1G (GEL)

Int Cl (Ed.7): G01V 1/28, 1/30, 1/36, 1/38

Other: Online WPI, EPODOC, JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	WO 01/01170 A1 (CONTINUUM RESOURCES CORP)	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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